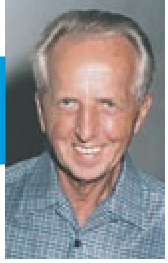

ACADEMIC STUDY
by Dr. David Kirk | Coventry University

Quantification of Shot Peening Intensity Rating

INTRODUCTION

This article is complementary to the previous TSP article– "Quantification of Shot Peening Coverage." As such, it considers the second of the two most important shot peening requirements specified by customers. "Peening Intensity" as a phrase is ambiguous, since most engineering and scientific intensity quantities refer to something per unit area. Addition of "rating" yields "Peening Intensity Rating" (PIR) as a disambiguous quantity. "Rating" implies the application of some sort of criterion appropriate to the situation; e.g., golf rating, theatre rating, weather rating. The criterion for peening intensity is a particular point on a 'saturation curve'.

Shot peening intensity is rated by a point, P, on a 'saturation curve', see fig.1. This point has, of necessity, two coordinates – H and T. H is the 'h-coordinate' value of deflection at a 't-coordinate' value of peening time, T. The definition of 'T' is that the arc height increases by 10% when T is doubled. The magnitude of H on a particular curve therefore depends upon the location of T. Peening intensity rating increases with increase in the magnitude of H.

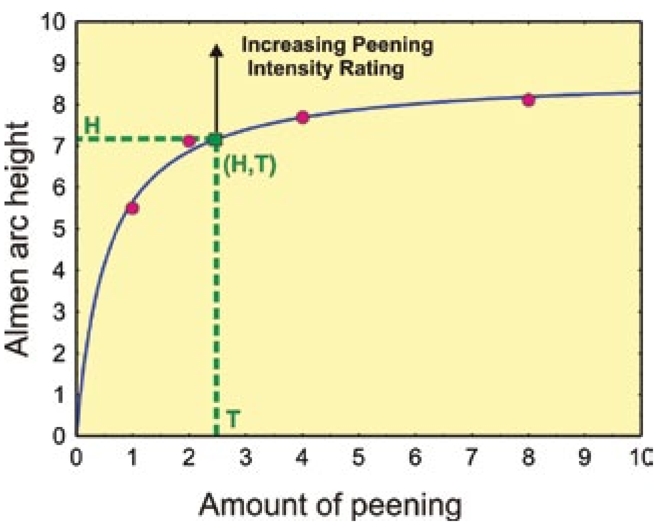

Fig.1. Typical peening intensity curve with derived Peening Intensity Rating, H.

Shot peening one major face of an Almen strip induces bending of the strip. This bending of the strip is created by the plastic extension of the peened face. It is sometimes stated, erroneously, that the strip bending is solely caused by residual compressive stresses in the peened surface layer. In creating strip bending, two mechanisms are involved. The first is plastic deformation of the surface being peened – which causes permanent bending. The second is a consequence of the first – residual compressive stress in the peened surface which causes further, semi-permanent, bending. Both of these mechanisms are beneficial to the service performance of components.

It has been shown (ICSP2, Kirk, "Behavior of Peen-formed Steel Strip on Isochronal Annealing") that the two contributions to strip bending (plastic deformation and residual compressive stress in the peened surface layer) are approximately equal in magnitude. This equality was indicated by the 50% reduction of arc height that occurs when peened Almen strips were stress-relieved by annealing. This effect is illustrated, schematically, by fig.2.

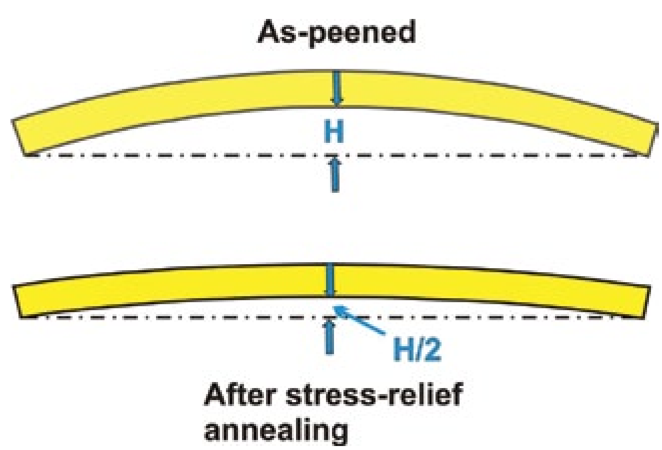

Fig.2. Halving of Almen strip deflection after stress-relief annealing.

BENDING OF ALMEN STRIPS

Bending of Almen strips, to generate arc height deflection, involves two components:

(1) **Permanent bending - due to the plastic extension of the peened surface** and

(2) **A removable bending moment - resulting from the residual compressive stress in the plastically-deformed surface layer.**

This bending moment, M, is illustrated by fig.3.

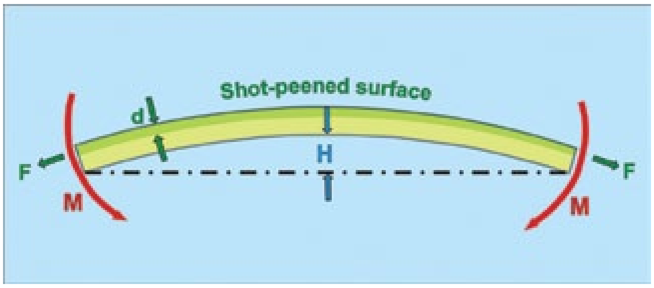

Fig.3. Bending of an Almen strip due to induced bending moment, M.

Plastic expansion of the peened surface (due to cold-working) extends to a depth, d. This forces the strip to bend - permanently. This bending is resisted by the strip, resulting in compressive residual stress to the depth, d. Compressive residual stress in the peened surface generates an outward force which contributes roughly half of the observed deflection, H.

The concept of a combination of permanent, plastic, bending and removable, elastic, bending is important for the rating of peening intensity – and for the whole process of shot peening. As a mental exercise consider the following analogy. A thin flat strip of aluminum can be bent, using two hands, to form an arc. If only small forces are being applied the strip is only suffering elastic bending and will return to its flat shape when the forces are removed. If, however, the applied forces reach a critical limit the strip will become permanently bent. Removing the applied forces will only reduce the bending. The strip will have suffered some permanent bending and will be left with compressive residual stress in the convex face.

Both of the bending components involve energy being stored in the peened surface – either as cold-work energy or elastic bending energy. Cold-work is force multiplied by distance so that its units are Nm. Bending moment, **M**, is force, **F**, multiplied by the distance through which that force acts – so that its units are also **Nm**. The distance involved is approximately that from half the depth of the compressed layer to the center of the Almen strip.

The units for work done are **N*m** (force multiplied by the distance through which it acts). Hence the work done in plastically deforming the strip surface has units of **N*m**. These are the same as those for the kinetic energy of impacting particles (as described in the previous TSP article). We know that the units for bending moment, **M**, are also **N*m** (again force multiplied by the distance through which it acts). Hence the units of the bending moment induced by compressive residual stresses are **N*m** - which are the same as those of the kinetic energy of the impacting particles and also for the work done as plastic deformation.

Arc height has a single unit - of distance, **m**. This is the deflection, **H**, at a particular point on an 'arc height versus amount of peening' curve. Hence:

$$\mathbf{H = M/K} \quad (1)$$

Where **M**, the kinetic energy that has been effectively absorbed, has units of **N*m** and **K** is a constant (for a given thickness of Almen strip) and has units of **N**.

ABSORPTION OF SHOT STREAM KINETIC ENERGY

We can estimate (a) the amount of kinetic energy that a given shot stream delivers to an Almen strip surface, (b) the amount of kinetic energy that is required to generate a known amount of bending of an Almen strip and (c) compare these quantities with one another.

(a) Amount of kinetic energy being delivered by a shot stream

A shot stream delivers a known amount of kinetic energy per second. This amount, **S**, is given by:

$$\mathbf{S = ½FR*v^2} \quad (2)$$

where **FR** is the feed rate.

Equation (2) is simply a version of the familiar ½m*v^2 expression for kinetic energy of a particle.

The total amount of kinetic energy, **TA**, provided in a given time, **t**, is therefore given by:

$$\mathbf{TA = ½FR*t*v^2} \quad (3)$$

where **FR** is the feed rate and **t** is the time of peening.

Assume, for the sake of argument, that a shot stream is delivering 0.02 kg of shot per second (1.2 kg per minute) whose velocity is 50 m*s^{-1}. Using equation (3) we get that when **t** equals 1 second:

$$\mathbf{TA = ½*0.02\ kg*s^{-1}*1s*50^2\ m^{2}*s^{-2}}$$
$$\mathbf{= 25\ kg*m^{2}*s^{-2}\ or}$$
$$\mathbf{TA = 25\ N*m}$$

This is the total amount of kinetic energy delivered by the shot stream in one second. Only a fraction of the shot stream actually impacts an Almen strip placed in its path. That fraction can, however, be estimated for a given geometry of the shot stream.

(b) Amount of kinetic energy required to generate a known amount of bending

Trying to estimate the required amount of energy using plasticity and elasticity theories simultaneously is complicated. The problem is greatly simplified by assuming that all of the required energy is for elastic bending. Alternatively we could estimate the energy required to elastically bend to a displacement **h/2** and then simply double that amount (to allow for the plastic deformation requirement).

Assume then that an Almen A strip is elastically bent to an arc height, **h**, of 0.250 mm. The bending moment (and hence amount of kinetic energy required) can be estimated by employing the standard beam-bending formula that **M = E*I/R** where **E** is elastic modulus, **I** is the second moment of area (width times thickness cubed divided by twelve for a rectangular strip). **R** equals $L^2/8h$ (for a circular arc) where **L** is the strip length. Substituting for **R** gives that:

$$M = E*I*8h/L^2 \quad (4)$$

Using **E** equal to 210 GPa, **h** equal to 0.250 mm and **L** equal to 40 mm, equation (4) predicts that:

$$M = 1.01\ N*m$$

(after multiplying by 1.125 to allow for cross-wise bending).

(c) Comparison of (a) and (b)

There is a very large difference between the 25 N*m of kinetic energy estimated for **TA** and the 1 N*m estimated for **M**. This confirms that only a small fraction of the kinetic energy available from the shot stream is converted into Almen strip bending. Three reasons are evident: (1) only part of a standard shot stream will actually strike the strip, (2) not all of the kinetic energy of the particles striking the strip is absorbed – some is retained as the kinetic energy of the rebounding shot and (3) most of the energy causing plastic deformation is converted into heat.

Let us assume that (1) that 80% of the shot stream strikes the strip, (2) 50% of the kinetic energy is retained as rebound energy and (3) that 90% of the absorbed energy is converted into heat. This gives that the shot stream's contribution to strip bending energy, **C**, is given by:

$$C = 25\ N*m \times 0.8 \times 0.5 \times 0.1 \text{ or}$$
$$C = 1\ N*m$$

This value of 1 N*m is now the same as that predicted for **M**. It must be confessed that this close similarity is not accidental – the assumed values were 'tailored to fit'. Nevertheless these values were not unreasonable. This example shows that we can equate shot stream energy supply and bending requirement for realistic practical examples.

PROGRESSIVE ABSORPTION OF SHOT STREAM KINETIC ENERGY

The absorption of shot stream kinetic energy increases with the time of its contact with an Almen strip. In other words the longer we peen the greater will be the amount of absorbed energy. The total amount of kinetic energy, **TA**, which is delivered by a shot stream in a peening time **t** is given by equation (3). If the bending force, **F**, increased at a constant rate then the arc height would also be predicted to increase linearly with peening time. This is obviously not the case – the rate of increase of arc height decreases with peening time – as is evidenced by the actual peening intensity curve given as fig.4.

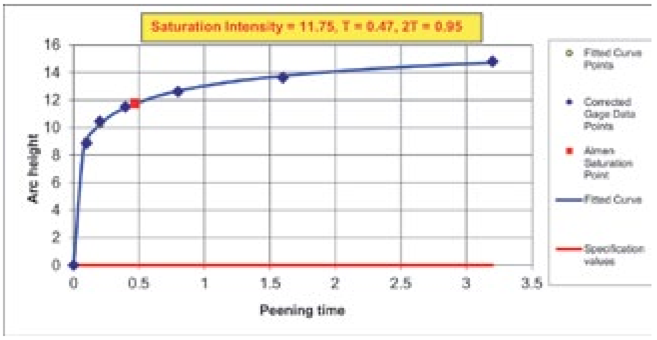

Fig.4. Typical Peening Intensity Curve.

The force, **F**, which creates bending due to residual stress, is given by:

$$F = \sigma * A \quad (5)$$

Where **σ** is the average residual stress in the peened surface layer and **A** is the cross-sectional area in the bending direction.

A bending moment, **M**, is generated by the force, **F**, acting over a distance **(t/2 – d/2)** where **d** is the depth of the compressed peened surface layer – see fig.5.

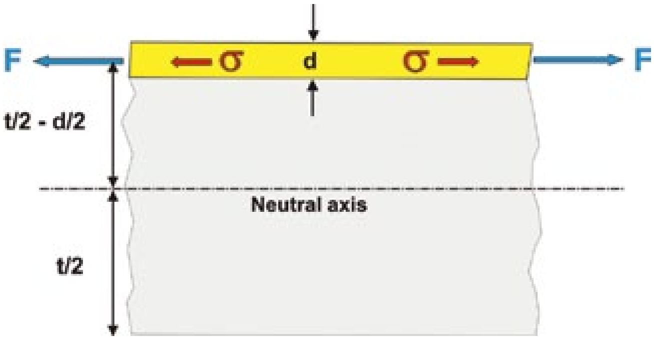

Fig.5. Section of peened Almen strip with bending force, F, acting over a distance (t/2 – d/2).

Strictly speaking, there are two bending forces at work: F_L acting in the longitudinal direction and F_T acting in the transverse direction. F_L promotes longitudinal bending whereas F_T promotes transverse bending.

The longitudinal bending moment, M_L induced by a compressed surface layer of depth, **d**, is given by $M_L = F*(t/2 - d/2)$ but $F = \sigma*A$ and $A = W*d$ (where **W** is the width of the Almen strip). Hence we have that:

$$M_L = \sigma*W*d*(t/2 - d/2) \quad (6)$$

For the transverse bending moment, M_T, with a strip of length **L** the equivalent equation is that:

$$M_T = \sigma*L*d*(t/2 - d/2) \quad (7)$$

AVERAGE LEVEL OF RESIDUAL STRESS IN COMPRESSED SURFACE LAYER

The average level of residual stress is a very important quantification parameter – determining both the magnitude of component property improvement and the degree of either beneficial or unwanted component distortion. In order to estimate this average stress we must first know the residual stress profile – just as we must establish a saturation curve before we can estimate peening intensity. Analyzing a residual stress profile for average stress is best carried out by estimating the area of the residual stress profile and dividing that area by the depth of the compressed layer. Three applicable techniques are described in this section. They are: Direct Graphical Analysis, Computer-based Graphical Analysis and Calculus-based Graphical Analysis.

Direct Graphical Analysis

This method is based on summing the number of unit rectangles that lie within the area to be estimated. The unit's size must be small compared with the area being estimated – to ensure reasonable accuracy. Fig.6 shows a unit rectangle as the 'counting unit'. The area of the unit shown happens to be -50 Nmm^{-2} (depth) multiplied by 0.02mm (width). That area is therefore exactly -1 Nmm^{-1}. It can be seen in fig.6 that the area of the profile comprises a mixture of (a) units that lie completely within the area and (b) units overlapping the stress profile so that they are part inside and part outside. The trick is to add half of these overlapping units to all of those completely within the area. As an example consider the top row of unit rectangles in fig.6. There are 23 unit rectangles completely within the area and 2 that are only partly within the area – hence we count that row as 24 (23 plus 2/2). Successive rows count up as 23, 22, 21, 19, 19, 17, 17, 15, 14, 12, 10, 6 and 1. Adding up the 14 row counts gives 220 units as an estimate of the profile's area.

The average residual stress in the profile σ_{AV} is obtained by dividing the measured area by the width, **d**, of the profile. For this example **d** is 0.5mm. Hence the average residual stress is - 440 Nmm^{-2} (- 220 Nmm^{-1} divided by 0.5mm).

Computer-based Graphical Analysis

This method uses advanced mathematical software (such as the author's favorite – "MathCad") but requires an input of the equation that defines the residual stress profile. In a previous article by the author ("Curve Fitting for Shot Peening Data Analysis", TSP, Spring, 2002) it was shown that the normal shape of a stress profile can be assigned a simple cubic equation. Fig.15 of that article is recreated here as fig.6 – albeit with some additions to emphasize area estimation. The equation of this particular residual stress profile is that:

$$\sigma = -1.3336*10^4*x^3 + 1.4669*10^4*x^2 - 3000.5*x - 500 \quad (8)$$

where **x** is the distance below the surface.

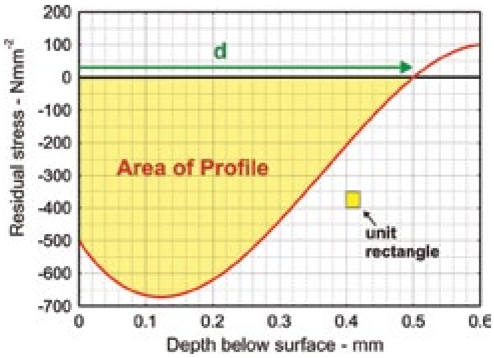

Fig.6. Residual stress profile emphasizing profile area and unit rectangle.

Having inputted the equation of the residual stress profile the computer program is then told to sum the area between limits of 0 and 0.5. Using the summing facility of "MathCad" the area is given as -222.2 units which on dividing by 0.5 (as in the previous method) estimates the average residual stress to be -444.4 Nm^{-2}. That is only 1% different from the partially-subjective method used previously and has the advantage of being completely objective. The summing facility that the computer uses is exactly the same as that of the direct graphical analysis method – the difference being that the 'unit rectangle' is relatively minute to that many millions of units are summed in a fraction of a second.

Calculus-based Graphical Analysis

This method also requires knowing an equation that defines the residual stress profile. The equation is then 'integrated'. For equation (8) the integral is:

$$\sigma = -1.3336*10^4*x^4/4 + 1.4669*10^4*x^3/3 - 3000.5*x^2/2 - 500x \quad (9)$$

The area defined by the integral equation (9) is obtained by simply substituting 0.5 for **x**. This gives that the estimated area is -222.2 – exactly as estimated using computer software – yielding -444.4 Nmm^{-2} as the average residual compressive stress.

QUANTIFICATION OF ARC HEIGHT DUE TO RESIDUAL STRESS

Equations (6) and (7) can now be used to derive an equation for that part of the arc height that is due to residual stress. This derivation uses the relationship that **M = E*I/R** where **E** is elastic modulus, **I** is the second moment of area (width times thickness cubed divided by 12 for a rectangular strip) and **R** is the radius of bending together with the relationship between arc height, strip dimension and **R** described in previous articles. Substituting those relationships into equations (6) and (7) gives that:

$$h_L = 1.5*\sigma*L^2*d*(t/2 - d/2)/(E*t^3) \quad (10)$$

and

$$h_W = 1.5*\sigma*W^2*d*(t/2 - d/2)/(E*t^3) \quad (11)$$

where h_L and h_W are the contributions to arc height from longitudinal and width-wise bending respectively, σ is the average residual compressive stress, **L** and **W** are the longitudinal and width-wise distances between the ball supports of the Almen strip and **t** is the strip thickness.

Adding h_L and h_W gives us the total arc height deflection **H** (that measured by an Almen gage). Hence:

$$H = 1.5*\sigma*(L^2 + W^2)*d*(t/2 - d/2)/(E*t^3) \quad (12)$$

The longitudinal and width-wise distances, **L** and **W**, are fixed quantities as is the thickness, **t**, of a given type of Almen strip. Hopefully, the elastic constant, **E**, is also a fixed quantity. Using **L = 31.75 mm**, **W = 15.87 mm**, **E = 210,000 Nmm^{-2} and t = 1.295 mm** (the thickness of Almen A strips) equation (12) simplifies to:

$$H_A = 4.144*\sigma*d*(0.6475 - d/2)/1000 \quad (13)$$

If the average compressive stress is independent of the depth then equation (13) predicts that the arc height stress contribution will only depend on the depth, **d**, of the profile. Fig.7 plots the equation, together with the curves for Almen N and C strips, assuming a constant average compressive stress of 400 Nmm^{-2}. The curves indicate several significant features. These include: (1) that the arc height rises in a parabolic fashion with increasing layer depth reaching a maximum when the depth is half the strip's thickness – thereafter the arc height falls as some force is now acting in the opposite bending direction, (2) the depth of layer for a given arc height is in the ratios 1:3:10.5 for N, A and C strips respectively.

It should be noted that the measured total arc height for a given peened Almen strip is increased because of the plastic deformation contribution to bending.

DISCUSSION

This article has used basic beam bending principles to quantify the relationship between the several factors affecting measured Almen arc height – and hence peening intensity. In spite of the simplifications that have been adopted the quantitative relationships that have been derived tally with practical experiences.

Equation (12) epitomizes the several factors that quantitatively influence derived Almen peening intensities. Measurements of arc height, **H**, are affected by the precision and bias of the measuring technique; the distances between the gage ball supports, **L** and **W**, are critical and ball wear is an established concern; strip thickness, **t**, appears in both numerator and, as a cube, in the denominator; elastic modulus, **E**, controls **H** inversely (but is not included in strip specifications) and by the average stress, σ, in the compressed surface layer. Converting a set of **H** measurements into a 'saturation curve' and deriving the peening intensity point have been thoroughly discussed in other articles in this series.

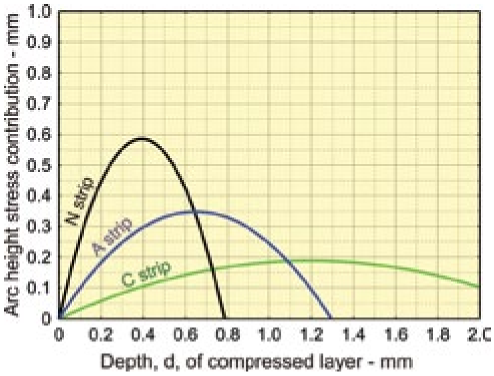

Fig.7. Contribution to arc height due to residual compressive stress.

Measurements of the average stress in the compressed surface layer are not commonly available – unfortunately, since equation (12) assumes that measured arc height is directly proportional to the level of stress. Equations (6) and (7) indicate that the peening-induced bending moment (and hence arc height) are directly proportional to the depth of the compressed surface layer.

Some interesting graphical evidence is available: "Depth of Compression versus Peening Intensity" (EI Library of graphs). This indicates that the depth of compression is linearly related to the peening intensity. The converse must therefore be true – that peening intensity is proportional to the depth of the compressed layer. Fig.8 interpolates some of the information in the graph (which includes three steels of different hardnesses) to highlight the significance of Almen strip hardness variation. The graph converts the published data into metric units and uses the data up to its maximum (for three steels) of 0.711 mm (0.028A).

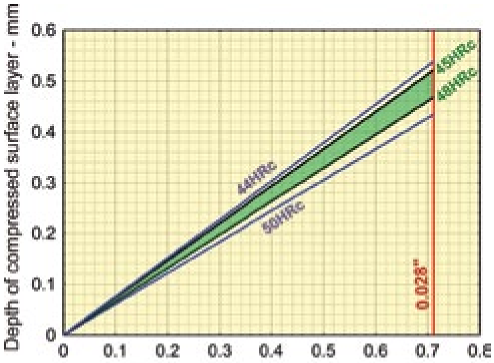

Fig.8. Derived variation of Peening Intensity with Almen Strip Hardness.

Specifications allow a range of 45 to 48 HRc for Aero-grade Almen strips and 44 to 50 for Auto-grade Almen strips. It can be seen in fig.8 that the higher-grade strips reduce the consequent variation of the derived peening intensity value by a factor of two. More direct experimental work is, however, needed in order that the several equations in this article can be substantiated.